Renewable and Sustainable Energy Reviews 15 (2011) 1042–1049

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Mine ventilation air methane as a sustainable energy source

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ARTICLE INFO

Article history:
Received 23 June 2010
Accepted 12 November 2010

Keywords:
Global warming
Greenhouse gases
Methane
Coal mines
Ventilation air

ABSTRACT

Underground coal mines emitting large quantities of methane to atmosphere is one of the sources of methane. Approximately 70% of the methane emitted from coal mines is released as the ventilation air methane (VAM). Unfortunately, due to the low methane concentration (0.1–1.5%) in ventilation air, its effective utilization is considerably low. However, the global warming potential of methane can be reduced up to 95% by oxidizing the methane. Energy recovery may be possible as the products of oxidization. In this study, the existing and developing methods, based on the oxidation of methane, are introduced with a discussion of the features of the methods of the mitigation and utilization of VAM. The main operational parameters of the methods such as combustion method, technical feasibility and engineering applicability were also discussed.

Contents

1. Introduction

Greenhouse gases are released mainly from the activities such as burning of fossil fuels, industrial processes, transportation, agricultural facilities and waste management processes. Accumulation of greenhouse gases in atmosphere has led to the increase of earth's temperature. As a result of the increases in global temperatures, it is expected that important changes affecting socioeconomic sectors, ecological systems and humans' life would come into existence [1,2].

Carbon dioxide, methane, nitrogen oxide and chlorofluorocarbons have vital importance on the global warming and the related environmental problems. Carbon dioxide has solely a rate of 74% in total anthropogenic greenhouse gas emissions. Methane, nitrogen oxide and high global warming potential gases follow carbon dioxide (Fig. 1).

Methane can trap the heat about 20 times of CO_2. In spite of the fact that methane is the second biggest contributor to anthropogenic greenhouse gas emissions, it affects climate changes at least as carbon dioxide does [5,6]. The variation of non-

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1364-0321/$ – see front matter
doi:10.1016/j.rser.2010.11.030

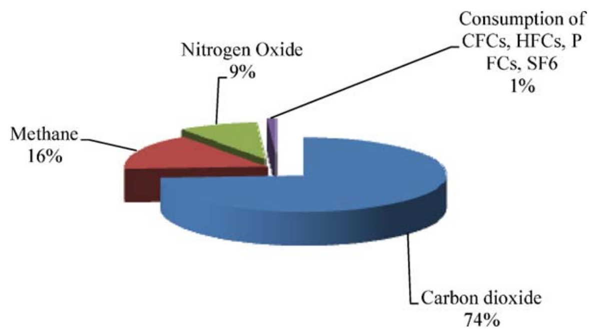

Fig. 1. Contribution of gases to anthropogenic greenhouse gas emissions [3,4].

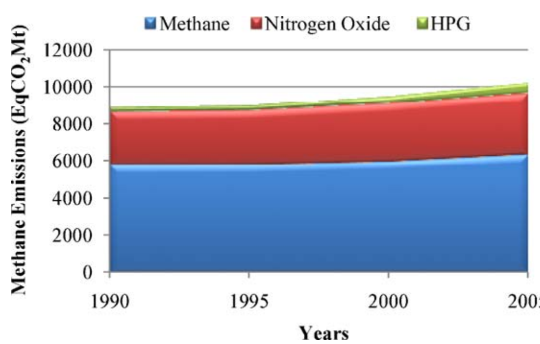

Fig. 2. Changes of non-CO_2 greenhouse gases between 1990 and 2005 ($EqCO_2Mt$) [5,8].

CO_2 greenhouse gases has been given in Fig. 2 between 1990 and 2005. Methane emissions have been increased gradually in 1990–2005 period and these increases are expected to keep their trend in the future. Estimated increase is about 12–16% for major contributing sectors as coal mining and agriculture by 2020 [7].

Methane is released mainly from agriculture, energy, industry and waste processing sectors. Energy sector is the second biggest contributor (30%) to anthropogenic methane emissions. Activities causing methane emissions in energy sectors include oil and natural gas systems; coal mining, stationary and mobile combustion and biomass combustion [9]. Emissions from coal mining account for 22% of emissions from energy sector (Fig. 3).

The quantity of gas emitted from mining operations is a function of two primary factors as coal rank and depth of seam. Coal rank is a measure of the carbon content of the coal. Higher coal ranks mean to higher carbon content and generally the higher methane content. Coals such as anthracite and semianthracite have the highest coal

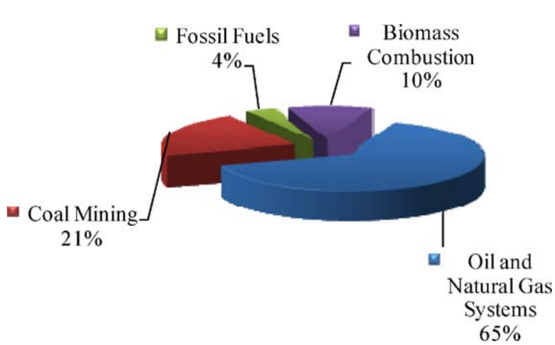

Fig. 3. Contribution of activities to methane emissions from energy sector in 2005 [5].

ranks, while peat and lignite have the lowest. The importance of the depth of coal seam is related with the pressure over the coal. Pressure increases with depth, preventing methane from migrating to the surface. Thus, underground mining operations typically emit more methane than surface mining [5,10].

Methane content of coal seams increases with depth. It is 0.02 m^3 per tonne of coal for coal beds under 100 m of surface. The methane concentrations increase up to 7.069 m^3 per tonne of coal at seams at 2000 m depth below the surface [11]. Singh et al. [12] developed a correlation for Indian coal seams. They found that the methane content of the coal seam increases 1.3 m^3 by 100 m increase of depth.

Methane is liberated during coal extraction and diluted through ventilation fans. The diluted methane is discharged to atmosphere via mine exhausts [13]. This gas is called "ventilation air methane (VAM)" and has very low methane concentration. The low concentration of methane in VAM is the result of the threshold limits of the methane concentration permitted in mine air. However, it is responsible for 60–70% of total methane emissions related to coal mining [14,15].

In addition to its effect on the continuity of the production processes of coal mines, methane has its most important effect in global warming. Mitigation opportunities may be utilized to overcome its adverse environmental effects. Besides, methane can be utilized as an energy source. Among the major sources of methane emissions, coal mining has important share in methane emissions. In U.S. coal industry 42 bcf of methane content of coal mines was liberated through drainage systems [2]. About 100 bcf of methane liberated as ventilation air. This is the most identical case for the most of the coal mining practices in all countries. Therefore, the ventilation air can be considered as a primary methane emitting source.

This paper discusses the available and/or theoretically possible methane mitigation and utilization methods suitable for ventilation air methane projects. The methods are also compared with respect to their main operational parameters such as combustion method, technical feasibility and engineering applicability. Additionally, various VAM projects from all over the world are presented.

2. Mitigation and utilization of VAM

Methane in coal seams has to be recovered in order to both maintain the safety in working environment during the production process and use the captured gas in diverse areas of industries. The recovered gas may contain methane up to 95% [6]. A general classification of coal mine methane (CMM) mitigation and utilization methods is illustrated in Fig. 4.

The gas captured by the drainage methods has methane concentrations over 30% and this gas may be used in industry. However, the utilization of ventilation air containing very low methane is difficult owing to the fact that the air volume is large and variable in concentration [18]. In order to use in industry, the methane concentration of ventilation air has to be increased. Effective technology to increase methane concentration is yet not available but is being developed and majority of the efforts has been concentrated on the oxidation of methane in ventilation air. Methane is transformed to carbon dioxide by oxidation and energy production can be possible with the heat produced. As a result of the oxidation, the effect of methane on climate change can be reduced almost 20 times [19,16,20].

Oxidation methods for methane may be classified as thermal and catalytic oxidation from the standpoint of the kinetic combustion mechanisms. VAM is used as ancillary and principal fuel in these oxidation technologies [21,22].

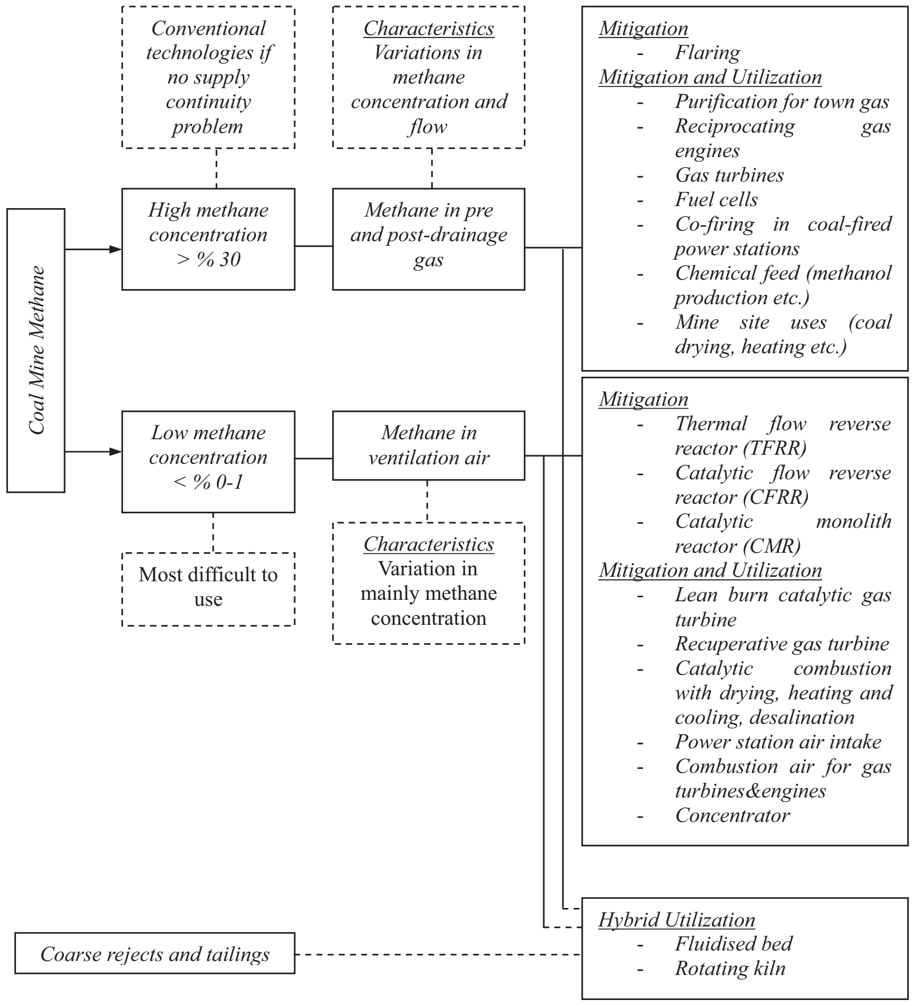

Fig. 4. Classification of coal mine methane mitigation and utilization methods [16,17].

3. Methane oxidation mechanisms

The overall combustion mechanism of methane may be represented by the following equation:

$$CH_4 + 2O_2 = CO_2 + 2H_2O \qquad \Delta H_{(298)} = -802.7\,\text{kJ/mol} \tag{1}$$

However, this is a gross simplification as the actual reaction mechanism involves many radical chain reactions [23,16]. The combustion of methane may produce CO or CO_2 depending on the methane ratio by the reactions below:

$$CH_4 + 2O_2 = CO_2 + 2H_2O \tag{2}$$

$$CH_4 + 3/2O_2 = CO + 2H_2O \tag{3}$$

Other reactions may also be present as following:

$$CH_4 + H_2O = CO + 3H_2 \tag{4}$$

$$2H_2 + O_2 = 2H_2O \tag{5}$$

$$CO + H_2O = CO_2 + H_2 \tag{6}$$

Catalytic combustion mechanism of methane is more complicated especially heterogeneous reactions taken into consideration. Possible mechanism for methane catalytic oxidation is shown in Fig. 5.

4. Ancillary uses of ventilation air methane

The captured ventilation air can be used as an ancillary fuel to increase the combustion performance in combustion processes. Basic applications utilizing the ventilation air methane as ambient air are pulverized coal-fired power stations, hybrid waste/coal methane combustion unit, gas turbines and internal combustion engines.

An assessment of ancillary uses technologies of ventilation air is presented in Table 1 with respect to the main operational parameters such as combustion method, technical feasibility and engineering applicability.

Energy recovery using these methods may be certain. The expected success is dependent mainly on the safe connection of these units to mine shafts. But, this is a site specific issue and has not yet been fully examined [16]. Table 2 compares the methods of the ancillary use of ventilation air methane from the standpoint of main operational parameters.

4.1. Pulverized coal-fired power station

Captured ventilation air can be utilized as ambient air at large power stations for the available combustion processes. A pilot scale study for this application has been conducted at a power station in Australia and the results have shown that the application of the method is technically possible especially if a power plant is already built near the mine exhaust shafts [14].

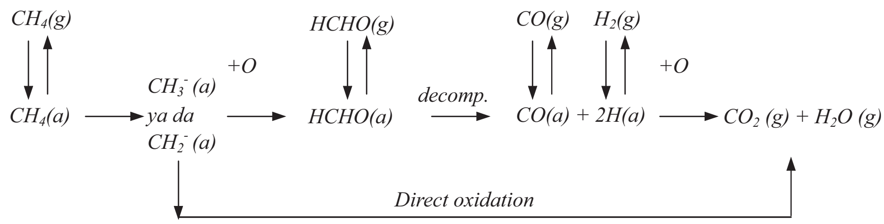

Fig. 5. A possible mechanism for methane catalytic oxidation: (a) adsorbed and gas phase [21].

Table 1
Mitigation and utilization technologies of ventilation air methane as an ancillary fuel [18].

Technology	Oxidation mechanism	Principal	Application status
Combustion air for conventional power station	Thermal	Combustion in power station boiler furnace	Mitigation/utilization. In a pilot scale unit but, large scale unit studies under consideration
Combustion air for gas turbines	Thermal	Combustion in conventional gas turbines combustor	Mitigation Utilization – studied
Combustion air for gas engine	Thermal	Combustion in a gas engine combustor	Mitigation Utilization – demonstrated
Hybrid waste coal/methane combustion in a kiln	Thermal	Combustion inside a rotating combustion chamber	Mitigation Utilization – being tried in a pilot scale unit
Hybrid waste coal/methane combustion in a fluidised bed	Thermal	Combustion inside a fluidised bed	Mitigation Utilization – being proposed as a concept

Power stations in general are not convenient to all gassy mines. This does not allow keeping the suitability of the method. Variation of methane concentration in ventilation air may affect the equipments' operational performances negatively depending on the methane concentration and flow rate. It also increases the complexity of power station operation. For instance, methane concentration in ventilation air could increase during combustion and it can result in damages to the equipment (boiler furnace, etc.) and slagging and residuals [16].

4.2. Hybrid waste/coal/tailings/methane combustion units

When considered the methane oxidation mechanism, it can be recognized that the use of ventilation air in hybrid waste/coal/tailings/methane combustion units in either rotating kiln or fluidised bed has similarities with the use of ventilation air in pulverized coal boilers. However, there is a need for additional regulations to organize the combustion process and provide the stability.

Some rotating kilns have been developed by several companies to hybridize waste/coal which is low quality. Studies carried out with these kinds of kilns have shown that high quality gas or fuel is required to maintain the stability of combustion process [23]. In a study conducted by Cobb [24], low performances were obtained in case of using hard coal wastes having high quality in these kinds of kilns.

Even though a wide range of pilot scale plant using VAM as an ancillary fuel in fluidised bed combustion units is available, there

Table 2
A comparison of methods of the ancillary use of ventilation air methane [16].

Technology	Feature	Combustion temperature (°C)	Technical feasibility and engineering applicability	Potential issues
Combustion air for conventional power station	Pulverized coal-fired furnace	1400–1650	Technically: yes	Limited sites
			Engineering: not demonstrated at a mine site	Potential operational problems to existing boilers
Hybrid waste coal/methane combustion in a fluidised bed	Fluidised bed	850–950	Technically: may be	Minimum requirement for coal/tailings quality
			Engineering: not demonstrated at a mine site	Proving tests needed for methane oxidation
Hybrid waste coal/methane combustion in a kiln	Rotating kiln	1200–1550	Technically: may be	Self-sustaining combustion
			Engineering: not demonstrated at a mine site	Minimum requirement for coal/tailings quality
Combustion air for gas turbines	Gas turbine	1400–1650	Technically: may be	Small percentage of turbine fuel
			Engineering: not demonstrated at a mine site	A lot of methane is emitted in by-passing air for a single compressor machine. If two compressor are used, there is increasing system complexity and decreasing capacity o using ventilation air
Combustion air for gas engine	Motor	1800–2000	Technically: yes Engineering: demonstrated at a mine site	Small percentage of engine fuel Using a small percentage of ventilation air

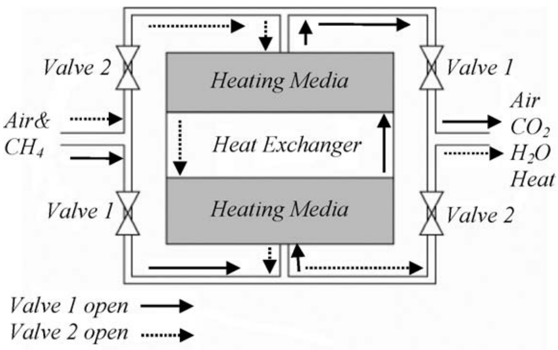

Fig. 6. A schematic illustration of thermal flow reversal reactor [5].

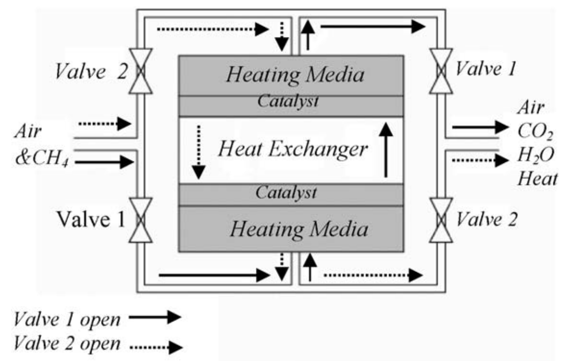

Fig. 8. A schematic illustration of catalytic flow reversal reactor [5].

has been no experimental study proving the methane will be fully oxidized in a fluidised combustion unit [25].

4.3. Internal combustion engines

Internal combustion engines commonly use medium quality gas to generate electric and; therefore, they are suitable for using VAM as ambient air in combustion processes. It is an option requiring low capital cost to reduce the methane in ventilation air if it has advantage in transportation. Due to the higher temperatures reached during combustion, it produces more N_2O gases than other methods do [14]. Despite the fact that the method has low capital cost; only, a small percentage of methane in ventilation air can be used in this application.

4.4. Conventional gas turbines

Conventional gas turbines have similarities with internal gas engines and a small percentage of methane in ventilation air meets the gas turbine's fuel needed. On the other hand, using of ventilation air to dilute the combustion process and cool the turbine results in the methane passing through the turbine without combustion. To avoid this, not only more complex turbine systems requiring compressed air from other sources are required but also compressed ventilation air is needed [26,16].

5. Principal uses of VAM

Ventilation air can be used as principal fuel in combustion processes for mitigation and utilization of methane in vented air. However, the principal uses of ventilation air may not be possible for some methods in terms of methane concentration for the operational requirement. Mitigation and utilization methods of VAM as a principal fuel are presented in Table 3. Ventilation air could be used in thermal and catalytic flow reverse reactors, catalytic-monolith reactors, lean burn gas turbines, concentrators. Detailed descriptions of these technologies are below.

5.1. Thermal flow reversal reactor technology (TFRR)

Thermal flow reversal reactors are the equipments used for thermal oxidation processes of organic components. Their operating principles have been described by a number of researchers [26,27]. Basically, a TFRR consists of a bed of a silica gravel or ceramic heat-exchange medium with a set of electric heating elements in the center. Mine ventilation air containing methane enters to the reactor through valves or channel available on the equipment [28]. A schematic illustration of TFRR is shown in Fig. 6.

Ambient temperature is required for autoignition of methane in ventilation air. Electrical heating elements in medium pre-heat the center of reactor to start the process with the aim of autoignition of methane. Ventilation air containing methane entering to reactor at ambient temperature, flows through the reactor in one direction and its temperature increases till oxidation of methane occurs near the center of the bed. The hot products of oxidation continue through the bed losing heat to the far side of the bed in the process. When the far side of bed is sufficiently heated and the near side has cooled because of the inflow of ambient-temperature ventilation air, the reactor automatically reverses the direction of ventilation airflow [21,5,22]. Ventilation air (VA) enters now the far side (heated) of the bed and then oxidation occurred. The hot gases transfer heat to the near side of the bed and exit the reactor at a temperature just modestly above ambient. Then, the process again reverses. Oxidized methane produces CO_2 and heat [29,30]. If meets demands, energy production can be possible from the oxidation products. Thermal flow reversal reactors oxidize ≥95% of methane in ventilation air mine (VAM) [31].

Thermal flow reversal reactors have alternative designs according to their cyclic of airflow and valves. The schematic illustrations of alternatives of TFRR are shown in Fig. 7 [31].

5.2. Catalytic flow reversal reactor (CFRR)

Catalytic flow reversal reactors differ from the TFRR in terms only of a catalyst used in CFRR method (Fig. 8). CFRR decreases the autoignition temperature of methane in ventilation air and

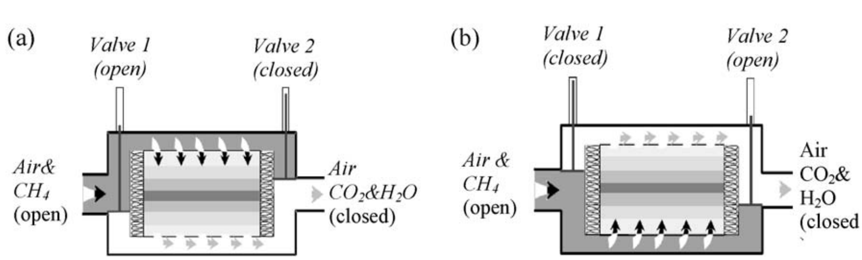

Fig. 7. Cyclic air flow alternatives in thermal flow reversal reactors (a) downward low and upward flow.

Table 3
Mitigation and utilization technologies of ventilation air methane as principal fuel [18].

Technology	Oxidation mechanism	Principal	Application
Thermal flow reverse reactor (TFRR)	Thermal	Flow reverse reactor with regenerative bed	Mitigation: demonstrated Utilization: not demonstrated yet
Catalytic flow reverse reactor (CFRR)	Catalytic	Flow reverse reactor with regenerative bed	Mitigation: demonstrated Utilization: not demonstrated yet
Catalytic-monolith combustor	Catalytic	Monolith reactor with a recuperator	Mitigation: demonstrated Utilization: not demonstrated yet
Catalytic lean burn gas turbine	Catalytic	Gas turbine with a catalytic combustor and recuperator	Mitigation: combustion demonstrated Utilization: being developed in a lab scale unit
Recuperative gas turbine	Thermal	Gas turbine with a recuperative combustor and recuperator	Mitigation: combustion demonstrated Utilization: demonstrated in a pilot scale unit but needed further modification
Concentrator	N/A, adsorption	Multi-stage fluidised/moving bed using adsorbent, and a desorber	Mitigation and utilization: under development

keeps the durability of system reaction during combustion [32]. Over heating or over cooling may be prevented by adding air or air–water mixer to the heat-exchanger [5,33]. These kinds of reactors have some advantages such as working at low temperatures, releasing low amount of N_2O (can be omitted), low production and engineering costs, requiring small equipments [34,35].

A study reported by Sapoundjiev and Aube [35], has shown that CFRR would be used for generating electric at coal mines being far away to thermal energy users. Discussing on the benefits from CFRR in spite of using in coal plants for mitigation of methane in VA, they stated that this method could be applied for reducing the methane emissions released from different fields. Fig. 9 shows the advantages of CFRR method using methane (0.5%) in VAM. One can understand from the figure that (1) the greenhouse effect of VAM would be decreased and (2) the products of oxidation can be used in diverse areas.

CFRR oxidizes approximately 90% of methane in VA. Thus, it allows obtaining an important energy source, reducing the greenhouse effect of VAM [36].

5.3. Catalytic-monolith reactors (CMR)

Somewhat similar principles which exist for the other methods, apply in operational and design characteristics of catalytic-monolith reactors. Catalytic-monolith reactor uses a monolithic reactor like a honeycomb. It is widely utilized because of its outstanding characteristics as very low pressure drop at high mass flows, high geometrical area and high mechanical strength [37]. Monoliths used consists of a structure of a parallel channels with walls coated by a porous support containing catalytically active particles. Thus, compared with the other reactor designs (TFRR or CFRR), it can be seen that the CMR unit is more compact in terms of processing the same amount of ventilation air, but will require a recuperator to pre-heat the ventilation air. Table 4 compares the different reactor designs (TFRR, CFRR and CMR) in terms of main performance and design characteristics.

VAM, captured at mine exhaust, not only has high volume and low concentration of methane but also its methane concentration is variable. These drawbacks can result in inefficient working of mitigation and utilization methods. MEGTEC, a firm which produced TFRR, has reported that TFRR unit can continue its function at concentration of 0.08% methane. However, a simulation results carried out at Utah University, have indicated that temperatures would drop below the minimum required if the methane concentration drops below 0.35% [14]. To sustain CFRR operation, the minimum methane in the ventilation air should be above 0.1%. It is unclear how long CFRR unit can be operated on 0.1% methane in air [33]. As a result of the experimental catalytic combustion work aimed to define the minimum methane concentration needed for operation of CMR, it was found that it can be operated when the methane concentration is greater than 0.4% in VAM [16].

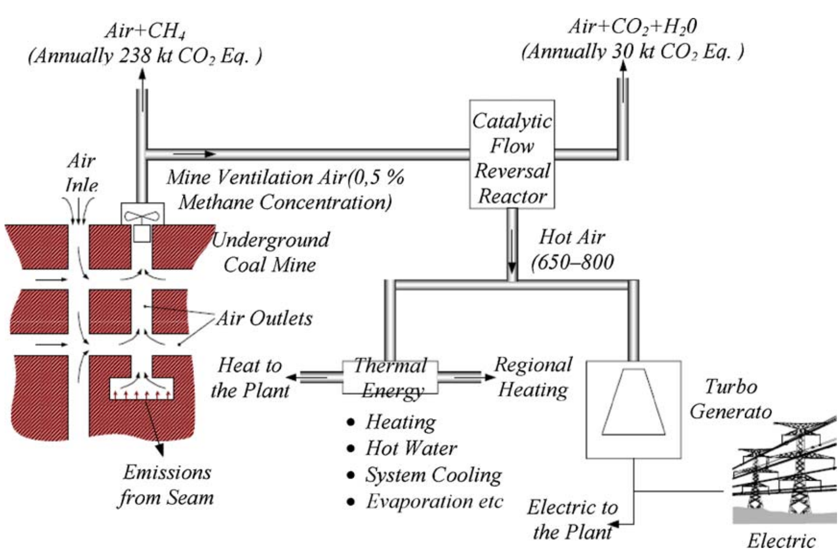

Fig. 9. Advantages of catalytic flow.

Table 4
Comparison of the reactor technologies (TFRR, CFRR and CMR) from the standpoint of their outstanding features [16].

Features	Thermal flow reversal reactor (TFRR)	Catalytic flow reversal reactor (CFRR)	Catalytic-monolith reactor (CMR)
Principles of operation	Flow reversal	Flow reversal	Monolithic reactor
Catalyst	No	Yes	Yes
Auto-ignition temperature	1000 °C	350–800 °C	500 °C
Cycle period length	Shorter	Longer	Continuously
Minimum CH_4 concentration	% 0,2	% 0,1	% 0,4
Applicability	CH_4 mitigation	CH_4 mitigation	CH_4 mitigation
Possibility of recovering heat to generate power	May need additional fuel to increase CH_4 concentration and maintain it constant	May need additional fuel to increase CH_4 concentration and maintain it constant	May need additional fuel to increase CH_4 concentration and maintain it constant
Variability of CH_4 concentration	Variable	Variable	Variable
Plant size	Huge	Larger	Compact
Operation	More complicated	More complicated	Simple
Life time	N/A	N/A	>8000 h for catalyst
NO_x emission	N/A	Low	Low (<1 ppm)
CO emission	Low	Low	Low (~0 ppm)

Table 5
Comparison of some features of Lean-Burn gas turbine technologies [16].

Features	EDL recuperative turbine	CSIRO catalytic turbine	IR catalytic micro turbine
Principles of operation	Air heater inside combustion chamber	Monolith reactor	Monolith reactor
Catalyst	No	Yes	Yes
Auto-ignition temperature	700–1000 °C	500 °C	N/A
Experience	Pilot-scale	Bench-scale study on combustion	Conventional micro turbine development
Cycle period length	Continuously	Continuously	Continuously
Minimum CH_4 concentration for operation	% 1,6	% 1	% 1
Applicability	CH_4 mitigation and power generation and need additional fuel to increase CH_4 concentration	CH_4 mitigation and power generation and need additional fuel to increase CH_4 concentration	CH_4 mitigation and power generation and need additional fuel to increase CH_4 concentration
Possibility of recovering heat	Feasible	Feasible	Feasible
Variability of CH_4 concentration	Constant	Constant	Constant
Operation	Simple and stable	Simple and stable	Simple and stable
Life time	May be shorter due to high temperature combustion heat exchanger	>8000 h for catalyst, 20 years for turbine	N/A
NO_x emission	Higher	Low (<3 ppm)	Low
CO_x emission	Low	Low (~0 ppm)	Low

5.4. Lean-burn gas turbines

In recent years, many lean-burn gas turbines are being developed such as EDL's recuperative gas turbine, CSIRO lean-burn catalytic gas turbine, Ingresoll-Rand micro turbine with a catalytic combustor [38]. VAM is mostly used in recuperative gas turbine using heat from the combustion process to pre-heat the air having methane. Comparison of some important features of lean-burn gas turbines is presented in Table 5. The methane concentration in ventilation air should be above 1.6%. Thus, it may require the addition of substantial quantities of methane to the ventilation air to reach the adequate methane concentration in order to be used as an ancillary fuel. Not only low concentration methane in ventilation air can be used in these kinds of turbines but also the methane captured from pre and post mining may be used [16].

A technical and economic assessment has been carried out on the implementation of 1% and 1.6% methane in gas turbines on the basis of real methane emission data from two Australian gassy coal mines [39]. As a result of this study, it has been concluded that 50–60% of the fuel for firing 1% methane catalytic turbine is the methane from ventilation air. On the other hand, it can be seen that 30–60% of the fuel for firing 1.6% methane catalytic turbine is the methane from ventilation air. Additionally, it has been determined that while almost 100% ventilation air was used for the turbines using 1% methane concentration, approximately 30–50% ventilation air was used for turbines using 1.6% methane concentration.

5.5. Concentrators

Concentrators are used to capture volatile organic compounds by a number of industries. These types of concentrators can enrich the methane in ventilation air and they provide the gas (methane) concentration required for the lean-burn gas turbines. Ventilation air containing 0.1–0.9% methane enters to these concentrators and leaves at a concentration of greater than 20% methane. If methane concentration is/or greater than 30% as a result of enrichment, ventilation air can be used to generate power using conventional gas turbines as well [16].

6. Conclusions

Methane is the second biggest contributor to anthropogenic greenhouse gas emissions. Its main sources are agriculture, marshes, oil and natural gas systems, coal mining and burning of fossil fuels. Coal mining is responsible for 7% of antrophogenic methane emissions. 70% of these emissions come from ventilation air at underground coal mines. Methane discharged into atmosphere may be considered as a contribution for the adverse effects of GHGs. Additionally, an energy source can be wasted. As a GHG, ventilation air methane is a contribution for the ineffective use of the world's energy produced. Mitigation and utilization methods may help to reduce methane content in atmosphere. In addition, a wasted source of energy could be utilized.

Effective method for mitigation and utilization of ventilation air methane is not yet available but many efforts have been devised in recent years. Majority of works has been concentrated on the oxidation of methane in ventilation air. The following conclusions can be drawn from the analysis of the current technological possibilities and the theoretical bases:

(i) Methane gas captured by drainage methods can be utilized depending on the methane concentration. However, it is so difficult to use mine ventilation air since it has high volume and contains low and variable concentration of methane.
(ii) VAM can be used as ancillary and principal fuel in combustion processes for the purposes of mitigation and utilization. Ancillary uses of ventilation air methane serve mainly in reducing the greenhouse effect of methane. In principal use, both the energy production and the greenhouse effect reducing goals may be achieved.
(iii) In case of inadequate methane concentration in ventilation air to meet the demands for the mitigation and utilization processes, ventilation air should be enriched to increase methane concentration. Concentrators are suitable devices for enrichment of low methane in ventilation air. After enrichment if methane concentration is greater than 30%, it can be possible to use it for power generation in conventional gas turbines.
(iv) The applicability of mitigation and utilization methods for VAM at any mine site depends mainly on site specific conditions. It is very important to investigate any possible safety issue when any type of technologies is connected to the mine site (mine exhaust).
(v) Globally the effect of methane from underground coal mines via ventilation air on climate changes could be reduced about 95% by using oxidation methods. On the other hand emissions from coal mining could be reduced to 67%.

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